

# REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)  [2] ABSTRACT: The objective of this program is to understand the effects of space radiation on multiple-quantum-well (MQW) photonic devices through a coordinated program of experimental characterization, analysis, and modeling. The work has focused on MQW laser diodes. Photonic devices based on MQW technology are widespread in both commercial and military applications. Such devices and systems offer an ideal opportunity for understanding the effects of the space radiation environment on nano-structures and provide insight into the physics of radiation effects on a class of devices that will revolutionize future electronic and optoelectronic systems. In this program, we have looked at proton-irradiation effects in MQW laser diodes, quantum dots, and high-electron mobility transistors. Irradiation has been performed using high-energy protons because they produce both long-term ionization damage and displacement damage.				
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## AFOSR FINAL REPORT 9/1/00

### [1] COVER SHEET:

Title:

Physics of Space Radiation Effects in Multiple Quantum Well Photonic Devices

Grant Number:

F49620-96-1-0217

PI name:

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Institution:

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Department of Electrical and Computer Engineering

The Optical Sciences Center

Tucson, AZ 85721

[2] ABSTRACT: The objective of this program is to understand the effects of space radiation on multiple-quantum-well (MQW) photonic devices through a coordinated program of experimental characterization, analysis, and modeling. The work has focused on MQW laser diodes. Photonic devices based on MQW technology are widespread in both commercial and military applications. Such devices and systems offer an ideal opportunity for understanding the effects of the space radiation environment on nano-structures and provide insight into the physics of radiation effects on a class of devices that will revolutionize future electronic and optoelectronic systems. In this program, we have looked at proton-irradiation effects in MQW laser diodes, quantum dots, and high-electron mobility transistors. Irradiation has been performed using high-energy protons because they produce both long-term ionization damage and displacement damage. Some of the key results are: (1) Proton-induced damage in MQW laser diodes is dominated by introduction of non-radiative recombination centers. The result is an increase in the threshold current, but the slope efficiency does not change significantly at typical fluences. (2) Proton-induced damage in MQW laser diodes exhibits complex temporal dependence because of in-situ and post-irradiation annealing. The annealing process is characterized by three different time constants, corresponding to different types of defects. (3) Proton-induced damage in MQW laser diodes is nearly independent of energy in the range studied (between 50 and 200 MeV), as is the non-ionizing energy loss. This differs from results obtained from GaAs laser diodes and resistors. (4) A model for radiation-induced damage in bulk and MQW laser diodes has been developed that agrees with the experimental data. (5) The photoluminescence signal from Ge/Si quantum dots can be completely destroyed by proton irradiation, but it recovers partially after thermal annealing. (6) Proton irradiation seriously degrades the saturation current and transconductance of  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  high-electron mobility transistors. Rapid thermal annealing at 800 C causes the devices to recover. (7)

Measurements of spectral changes in the output of proton-irradiated MQW laser diodes were made. The variation in the wavelength was relatively small, but in one case it shifted by about 1 nm. This is significant for potential applications.

[3] TECHNICAL PROJECT SUMMARY: An outline of the research tasks completed during the period of this contract is given below. The detailed results associated with each of these tasks have been reported in AFOSR technical progress reports as well as numerous journal publications and student theses. A comprehensive list of these is also provided below. Recent results that are not yet available in the public domain have been included as an attachment to this report.

#### 1. Proton Effects on MQW Laser Diodes

- (a) Quantified threshold current damage factor for various fluence/energies.
- (b) Characterized bias and orientation effects.
- (c) Discovered useful annealing behavior in damaged MQW laser devices.
- (d) Correlated novel post-anneal IV behavior with optical power increases.

#### 2. Proton Irradiation Effects on Ge Quantum Dots

- (a) Experimentally evaluated Ge quantum dots under various proton irradiation conditions.
- (b) Demonstrated both loss and recovery of photoluminescence from Ge dots.
- (c) Compared buried and surface dots with irradiation effects on quantum wells and quantum wires.

#### 3. Laser Simulation

- (a) Developed defect model for proton-induced damage.
- (b) Investigated defect impact on various physical parameters.
- (c) Discovered nonlinear dependence of threshold current on damage factors.
- (d) Validated simulation model through extensive experimentation.

#### 4. Proton-Irradiation Effects on High-Electron Mobility Transistors

- (a) Quantified the degradation of saturation current and transconductance with proton irradiation in HEMT devices.
- (b) Performed annealing study and explained recovery for various experimental conditions.

#### [4] PUBLICATIONS:

[1] Y. F. Zhao, A. R. Patwary, R. D. Schrimpf, M. A. Neifeld, and K. F. Galloway, "200 MeV Proton Damage Effects on Multi-Quantum-Well Laser Diodes," IEEE Trans. Nucl. Sci., vol. 44, pp. 1898-1905, 1997.

[2] Y. F. Zhao, R. D. Schrimpf, A. R. Patwary, M. A. Neifeld, A. W. Al-Johani, R. A. Weller, and K. F.

Galloway, "Annealing Effects on Multi-Quantum-Well Laser Diodes after Proton Irradiation," IEEE Trans. Nucl. Sci., Vol. 45, No. 6, pp. 2826-2832, 1998.

[3] Y. F. Zhao, R. D. Schrimpf, A. W. Al-Johani, M. A. Neifeld, R. A. Weller, and K. F. Galloway, "Energy Dependence of Proton Damage Effects on Multi-Quantum Well GaAs/GaAlAs Laser Diodes," manuscript in preparation.

[4] Y. F. Zhao, R. D. Schrimpf, K. F. Galloway, Y. S. Tang, D. Wang, and K. L. Wang, "Proton-Damage Effects on Germanium Quantum-Dot Structures," Appl. Phys. Lett., submitted for publication, 1998.

[5] S. J. Cai, Y. S. Tang, R. Li, Y. Y. Wei, W. G. Wu, L. Wong, K. L. Wang, M. Chen, Y. F. Zhao, R. D. Schrimpf, J. C. Keay, and K. F. Galloway, "Annealing Behavior of a Proton Irradiated  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  High Electron Mobility Transistor," IEEE Electron Device Lett., accepted for publication, 1998.

[6] S. C. Lee, Y. F. Zhao, R. D. Schrimpf, M. A. Neifeld, and K. F. Galloway, "Comparison of Lifetime and Threshold Current Damage Factors for Multi-Quantum-Well (MQW) GaAs/GaAlAs Laser Diodes Irradiated at Different Proton Energies," IEEE Trans. Nucl. Sci., Vol. 46, 1999.

[7] S. C. Lee, X. C. Wang, Y. F. Zhao, A. R. Patwary, R. D. Schrimpf, M. A. Neifeld and K. F. Galloway, "Simulation Model for Proton Damage of Multi-Quantum Well (MQW) Lasers," manuscript in preparation.

[5] THESES:

- [1] Ataur Patwary, "The Effects of High Energy Proton Irradiation on Multi-Quantum Well Laser Diodes," M.S. Thesis, University of Arizona Department of Electrical and Computer Engineering, 1998.

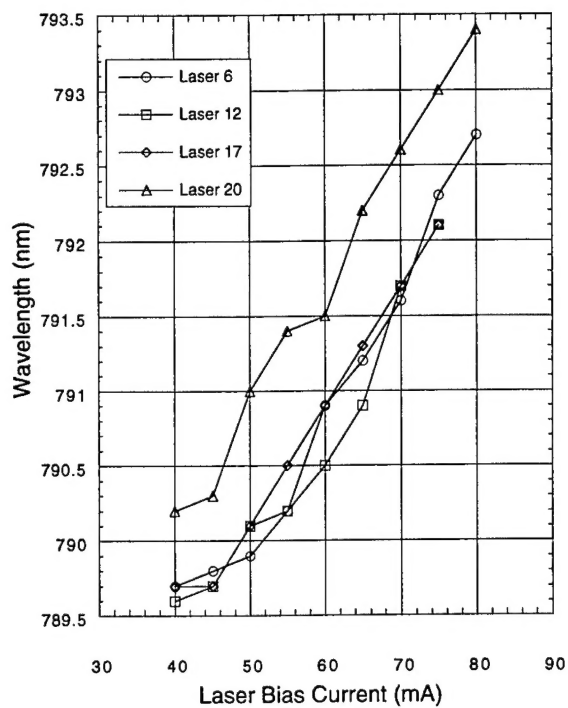
[6] PERSONNEL:

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- [2] Kenneth F. Galloway, Dean, Vanderbilt University (no charge)
- [3] Mark A. Neifeld, Associate Professor, University of Arizona
- [4] Yuanfu Zhao, Senior Research Associate, Vanderbilt University
- [5] Ataur Patwary, Graduate Student, University of Arizona
- [6] Tamera Anderson, Undergraduate Student, Vanderbilt University
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- [10] William Hasenplaugh, Graduate Student, University of Arizona

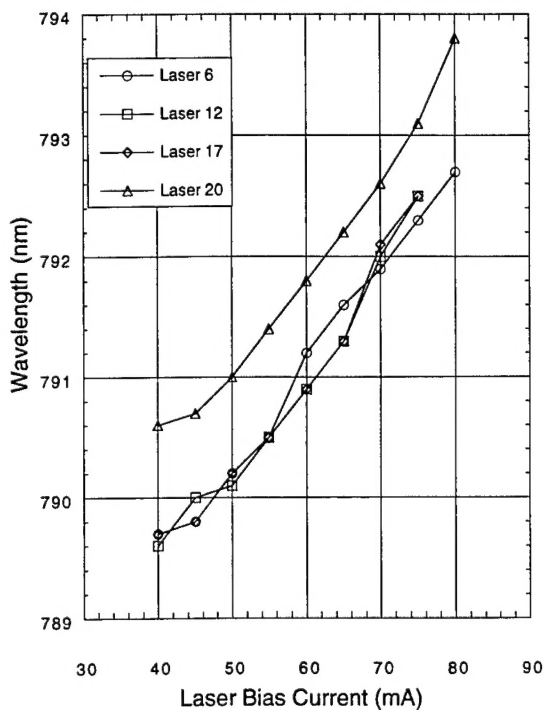
ATTACHMENT  
Recent Laser Diode Wavelength Measurements

During the no cost extension we have been working on measuring the effects of proton radiation on MQW laser wavelength. Our first task was to establish a measurement station for laser wavelength characterization. Temperature stabilization was found to be a critical feature of this apparatus. This is due to the strong wavelength variation with temperature exhibited by these laser devices. Using a Newport TE-stabilized laser mount together with an Anritsu optical spectrum analyzer, laser wavelength was measured as a function of drive current and temperature. Some results are shown in the figure below. From the data, it is clear that laser wavelength has been unaffected by all but one of the proton fluence levels studied. For this laser we find a roughly 1 nm departure from the expected operating wavelength. Further, this red shift is found to be consistent over a large range of operating temperatures and bias current levels. We should note that a 1 nm change in laser wavelength is consistent with a roughly 10 mA change in bias current or equivalently, a roughly 6 degree change in operating temperature. Although we believe that these variations can be significant in the context of OE system operation and especially in the case of fiber-based devices, at this time it is unclear which underlying physical mechanism is responsible for the wavelength shift (i.e., free carrier effects, bulk index variation, local temperature changes, etc.).

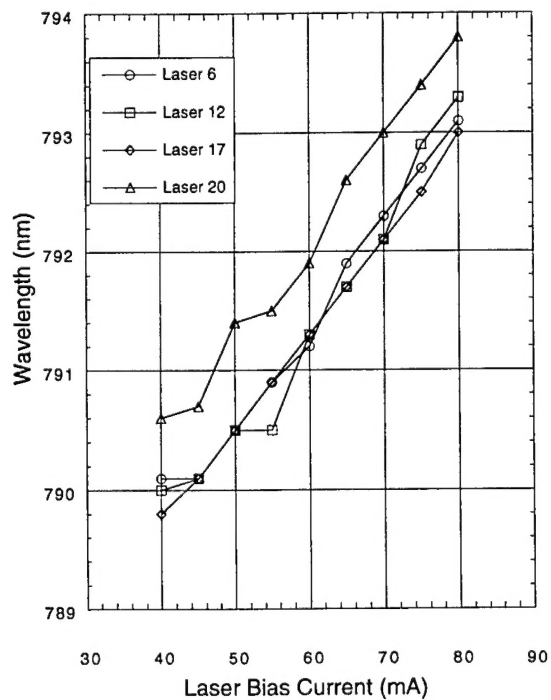
Wavelength Data for all Vandy Lasers  
T=17 C - increasing current trials



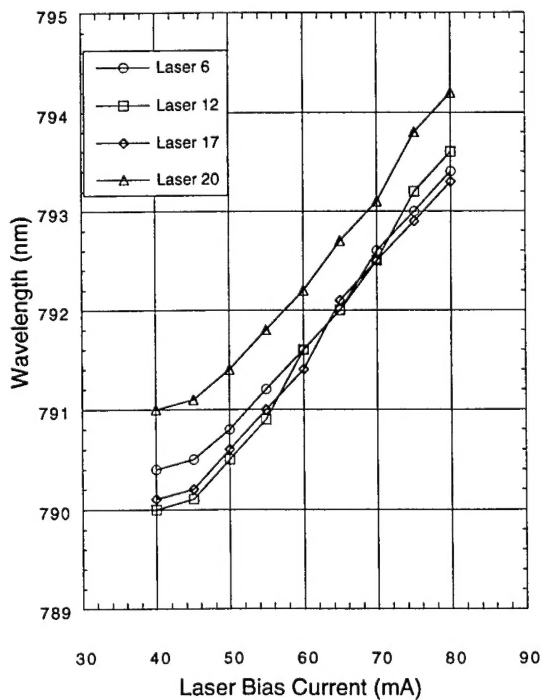
Wavelength Data for all Vandy Lasers  
T=18 C - increasing current trials



Wavelength Data for all Vandy Lasers  
T=19 C - increasing current trials



Wavelength Data for all Vandy Lasers  
T=20 C - increasing current trials



**1. Difference between the L-I History and Spectrum Analysis:**

Vandy L-I History	UA Spectrum
#12 not working	#24 not working
#6, #17, #24 can be regarded as the same group	#6, #12, #17 showed the same spectrum
#20, #21 can be regarded as the same group	#20 operates at 5nm longer wave length #21 operates at 10nm shorter wave length than #6,#12,and #17

**2. Irradiation Conditions & L-I changes after Irradiation**

Sample	Irradiation & Annealing	Threshold current shift after Irradiation
6	200 MeV, Bias 35 mA, Max fluence 1E14, Post-rad annealing 30 min @ short	~ 7 mA
12	100 MeV, 1E14 Irradiation + 30 min. Annealing with bias 40 mA (5E13 Irradiation + 30 min. Annealing with 18 mA)*2 times	Device dead
17	100 MeV, 5E13 Irradiation + 30 min. Annealing with Bias 1uA	~12 mA
20	100 MeV (low flux: 10 times less) 5E13 Irradiation + 30 min. Annealing with Bias 45 mA	~ 1 mA
21	100 MeV (low flux: 5 times less) 5E13 Irradiation + 30 min. Annealing with Bias 45 mA	~ 2 mA
24	200 MeV, Bias 1 nA, Max fluence 1E14, No post-rad annealing	~ 15 mA

